Prospects for a precision timing upgrade of the CMS PbWO$_4$ crystal electromagnetic calorimeter for the HL-LHC

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May 24, 2018
The CMS Electromagnetic Calorimeter (ECAL)

- Homogeneous, compact, hermetic, fine grain PbWO₄ crystals calorimeter
- Designed for excellent energy resolution ($< 1\%$ for 60 GeV $\gamma$)

- Divided in two regions:
  - **Barrel** (EB): $|\eta| < 1.48$, 61200 channels, APD readout
  - 2 **Endcaps** (EE): $1.48 < |\eta| < 3$, 14648 channels, VPT readout

- **Preshower** detector:
  - $1.65 < |\eta| < 2.5$
  - lead/silicon strips detector
  - aid $\pi^0/\gamma$ discrimination
The ECAL PbWO\textsubscript{4} crystals and readout

- Design ECAL requirements: time jitter $< 1$ ns to ensure good energy resolution

- PbWO\textsubscript{4} fast scintillator for an EM shower:
  - $\sim 90\%$ light emitted within 25 ns
  - $\sim 10\%$ contribution from Cherenkov emission

- Current pulse shaping optimized for the LHC conditions $\rightarrow$ to change at HL-LHC
  - 43 ns electronics shaping time
  - sampling at 40 MHz

- Arrival time information extracted from pulse shape
Single channel time resolution

Several contributions to single channel timing resolution:

- **Electromagnetic shower development fluctuations:**
  - longitudinal shower fluctuations
  - optical transit time spread

- **Photodetector + electronics**
  - photodetector rise and transit time
  - dark current rate and noise
  - electronics shaping time

- **DAQ clock distribution**
Current time resolution

- PbWO$_4$ crystals **intrinsic time resolution** measured at test beam:
  \[ \sim 20 \text{ ps constant term} \]

- In-situ measurements:
  - close-by crystals (same readout unit) of the same shower \( \sim 70 \text{ ps} \)
  - crystals in different clusters with Z→ee events \( \sim 150 \text{ ps} \)
The HL-LHC

- HL-LHC ultimate performance:
  - Instantaneous peak luminosity $L = 7.5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - $L = 4500 \text{ fb}^{-1}$ in 10 years
- 6 times higher level of radiation than at LHC
- Mean number of interactions per bunch-crossing from 50 $\rightarrow$ 200
- Degradation of object reconstruction performance
  $\rightarrow$ necessary upgrade of CMS sub-detectors

Event recorded during special high pileup fill with $\sim 100$ concurrent interactions
**CMS Upgrade overview**

**Trigger**
Track information at L1
- L1 Trigger latency 12.5 μs
- L1 output 750 kHz
- HLT output 7.5 kHz

**ECAL Barrel**
Upgraded electronics
Operate at lower temperature

**HCAL Barrel**
New electronics

**Muon System**
- Change DT and CSC barrel electronics
- Extend muon triggering to $\mu = 3$

**Endcap calorimeters**
- New High Granularity Calorimeter (HGC)
- Silicon sensors
- 3D reconstruction
- Timing information

**MIP Timing Detector**
- Barrel: LYSO crystals + SiPM
- Endcap: low gain avalanches diodes

**Tracker**
- Extended coverage to $\mu = 4$
- Higher granularity
- Reduction of material
- Selection of $p_t > 2$ GeV tracks for L1 trigger

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ECAL electronics **upgrade mandatory to meet HL-LHC L1 trigger requirements**

- **Increase latency**: $4.6 \, \mu s \rightarrow 12.5 \, \mu s$
- **L1 accept rate**: 750 kHz

ECAL electronics upgrade key points:

**Trigger**
- Provide **crystal by crystal information at L1 trigger** (currently 5x5 crystals granularity)
  - → enhance spike rejection
  - → improve objects identification

**Energy resolution**
- Reduce APD noise due to radiation damage
  - → cooling of crystals and photodetectors $18^\circ C \rightarrow 9^\circ C$

**Precision timing**
- Goal: **30 ps time resolution** for deposits with $E > 50$ GeV
  (photons from $H \rightarrow \gamma \gamma$ decay)
Keep the **same crystals and APDs**

**Replace Very Front-End (VFE), Front-End (FE) and off-detector electronics**

**Upgrade VFE electronics:**
- dual gain Trans Impedance amplifier (TIA)
- preserve a **fast signal** to optimize time resolution
- shorter **shaping time** (43 ns → 20 ns)

**ADC sampling** increased to **160 MHz**

**CMS clock distribution key role**
- ensure < 10 ps stability across CMS

More in talk by S. Pigazzini: "The CMS ECAL Upgrade for Precision Crystal Calorimetry at the HL-LHC"
Benefits from ECAL precision timing probed on H→γγ benchmark channel

- **Resolution on vertex z position < 1 cm**
  → negligible impact on m_{γγ} resolution
- Currently determined exploiting recoiling tracks: ε ~ 80 %
  → drop to ~ 30% at HL-LHC
- **vertex z determined via γ triangulation**
  → recover part of inefficiency: ε ~ 50 %

![CMS Projection](image-url)
Benefits from ECAL precision timing

Long-lived particles predicted by many BSM theories

- Several experimental signatures featuring delayed photons
- Simulation study performed on $\tilde{\chi}_1^0 \rightarrow \tilde{\gamma} + \gamma$

- Photon time of arrival exploited to identify the signal
- Analysis benefit from ECAL precision timing
  - Increase sensitivity to short lifetime and high mass neutralinos (green region in the plot)

![CMS Phase-2 Simulation](image)

- 300 ps: current TOF resolution
- 180 ps: TOF resolution with ECAL timing upgrade
- 30 ps: TOF resolution with MIP timing detector
Anomalous APD signal mitigation

- Hadron interaction in APD
  → anomalous signals (*spike*)
  → faster pulse than scintillation signal
  → exploit pulse shape for discrimination

**current readout**

![Graph showing current readout with markers for APD spike and signal]

**new TIA readout**

![Graph showing new TIA readout with markers for scintillation and spike]
Test Beam campaigns

- Test beam performed in 2015, 2016, 2017 @ CERN SPS
  → assess PbWO₄ intrinsic timing capabilities
  → test performance with the upgraded electronics

- 5x5 matrix of ECAL crystals + APD
- Different VFE configurations
- Signal readout by fast digitizer (CAEN V1742, 5 GS/s)
- Time information extracted from fit of the pulse shape

- Micro-channel plates (MCP) detector to provide time reference ($\sigma_t \sim 20$ ps)
- Time resolution extracted from gaussian fit of the $t_{MCP} - t_{crystal}$ distribution
2015 Test beam results: impact of shaping time

- Employed **current VFE electronics**
- Compared performance with current (43 ns) and reduced (21.5 ns) shaping time
  - Shorter shaping time $\rightarrow \sim$ factor 2 gain in $A/\sigma_{\text{noise}}$ (signal/RMS noise)
  - CMS in situ: $A/\sigma_{\text{noise}} \sim 800$ for a 50 GeV EM shower $\rightarrow \sigma_t < 50$ ps
2016 Test beam results with new electronics prototype

- Test performance of **prototype VFE with TIA component**
- Lower sampling frequency emulated at analysis level
  - → ultimate performance already with 160 MS/s sampling
- $\sigma_t \sim 30 \text{ ps for } A/\sigma = 250$
  - → 25 GeV at HL-LHC start (100 MeV noise)
  - → 60 GeV at HL-LHC end (250 MeV noise)
The HL-LHC will be a challenging experimental environment for the LHC experiments
   → CMS detector upgrade necessary to fully exploit the amount of data provided by the HL-LHC

Precision timing powerful means through which mitigate pileup effects

ECAL barrel electronics upgraded to cope with HL-LHC conditions:
   → possibility to include precision timing for high energy EM showers
   → goal: 30 ps time resolution for EM showers with \( E > 50 \) GeV

Intrinsic PbWO\(_4\) time resolution and performance of new readout tested at test beam
   → 30 ps time resolution achieved during test beams
Additional Material
Clock impact on ECAL time resolution

- Clock distribution checked exploiting laser system
- Many crystals illuminated at the same time across different readout units
- One crystal taken as reference ($t_{\text{ref}}$)
  \[ \rightarrow \] timing resolution from gaussian fit to $t_{\text{crystal}} - t_{\text{ref}}$
- Timing resolution of $\sim 40$ ps measured across whole ECAL
- Clock distribution instabilities between different readout units
  \[ \rightarrow \] $\sim 100$ ps shift in signal peak position
  \[ \rightarrow \] Instabilities occur after system resets

<table>
<thead>
<tr>
<th>CMS preliminary</th>
<th>ECAL Barrel</th>
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<tbody>
<tr>
<td>Blue laser, FWHM=20 ns</td>
<td>N: 47.97 ± 0.70</td>
</tr>
<tr>
<td>Green laser, FWHM=7 ns</td>
<td>C: 0.04251 ± 0.00055</td>
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<th>CMS preliminary</th>
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<tr>
<td>Same PLL region</td>
<td>N: 38.92 ± 1.20</td>
</tr>
<tr>
<td>Different PLL region</td>
<td>C: 0.04054 ± 0.00215</td>
</tr>
</tbody>
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Fit: \[ \frac{N}{Q_{\max}/\sigma_{\text{noise}}} + C \]
The CMS clock distribution

- Common CMS effort for precise clock distribution for Phase 2 upgrade
- Goal: 10-15 ps RMS jitter
- Two approaches being investigated:
  - LHC clock encoded within the lpGBT control links
  - dedicated clock fibers + fan-out chips
- Slow variation of phase monitored and calibrated in-situ from minimum bias events